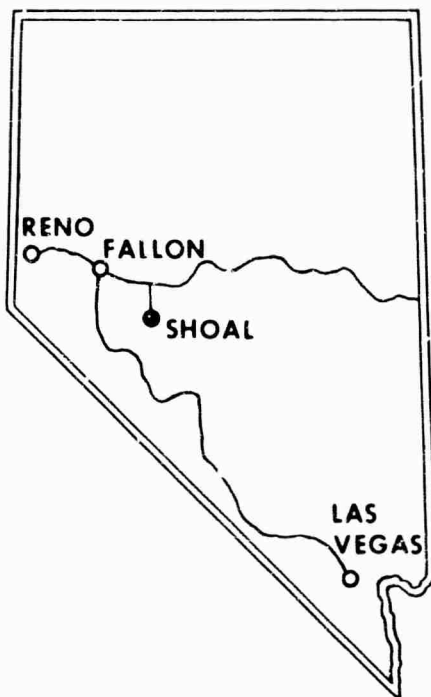


VELA UNIFORM PROJECT **SHOAL**

SPONSORED BY THE ADVANCED RESEARCH PROJECTS AGENCY OF THE
DEPARTMENT OF DEFENSE AND THE U.S. ATOMIC ENERGY COMMISSION

FALLON, NEVADA
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POST-SHOT HYDROLOGIC SAFETY
Hazleton-Nuclear Science Corporation

October 30, 1965

PROJECT SHOAL

Final Report

POST-SHOT HYDROLOGIC
SAFETY

October 30, 1965

Earth Sciences Division

HAZLETON-NUCLEAR SCIENCE CORPORATION
Palo Alto, California

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ABSTRACT

The Shoal Event, a 12.5 KT nuclear detonation, one in a series of tests in the Vela Uniform Program, occurred at 1000 hours PST on October 26, 1963, in the granite of the Sand Springs Range, about 45 kilometers southeast of Fallon, Nevada. The Sand Springs Range trends north-south and comprises jointed, faulted, and fault-bounded metamorphosed Paleozoic and Mesozoic marine sediments with a central granitic intrusive body. Alluvial-filled valleys, Fairview Valley and Fourmile Flat, are east and west of the Range, respectively. The alluvial fill in the valley contains and transmits appreciable quantities of ground water. Some ground water occurs in the granite and other crystalline rocks of the Range; however, this amount is small and movement is slow.

Re-entry drilling and Hydyme results indicate that the Shoal device detonated as predicted and a rubble chimney 26 meters in radius and 108.5 meters high was formed by the explosion. Significant quantities of radionuclides were produced at Shoal; however, nuclides in ground-water solution are not free to move from the rubble chimney region until aquifer stabilization is achieved and the chimney fills with ground water.

It is concluded that slow ground-water flow velocities and radioactive decay preclude the possibility of hazardous aqueous concentrations of radionuclides migrating more than one thousand meters from the

immediate detonation area. In addition, post-shot collection and analysis of water samples from the re-entry hole should continue on a regular basis.

Chapter 1

INTRODUCTION

1.1 OBJECTIVES

At the request of Nevada Operations Office, U. S. Atomic Energy Commission, under Contract No. AT(29-2)-1229, Hazleton-Nuclear Science Corporation (H-NSC) investigated safety aspects of ground-water contamination during the pre-shot, shot-time, and post-shot phases of Project Shoal. The objectives of the ground-water safety program are to ascertain the degree of ground-water contamination in the explosion zone and the extent of possible transport of contaminants by ground water, and, on the basis of these determinations, to evaluate the possible hazards involved and to recommend appropriate preventative and remedial measures.

1.2 BACKGROUND

Beginning in November 1961, the Desert Research Institute (DRI) and the Nevada Bureau of Mines (NBM), University of Nevada, explored the suitability of the Sand Springs Range, about 45 kilometers southeast of Fallon, Nevada, for possible use as the site of the proposed Project Shoal (Figure 1). Selection of the Sand Springs Range as the site of Project Shoal was made August 1, 1962, and a tentative ready date, June 1963, was established.

Preliminary geologic investigations indicated significant structural features in the granite core of the Sand Springs Range. The location of the

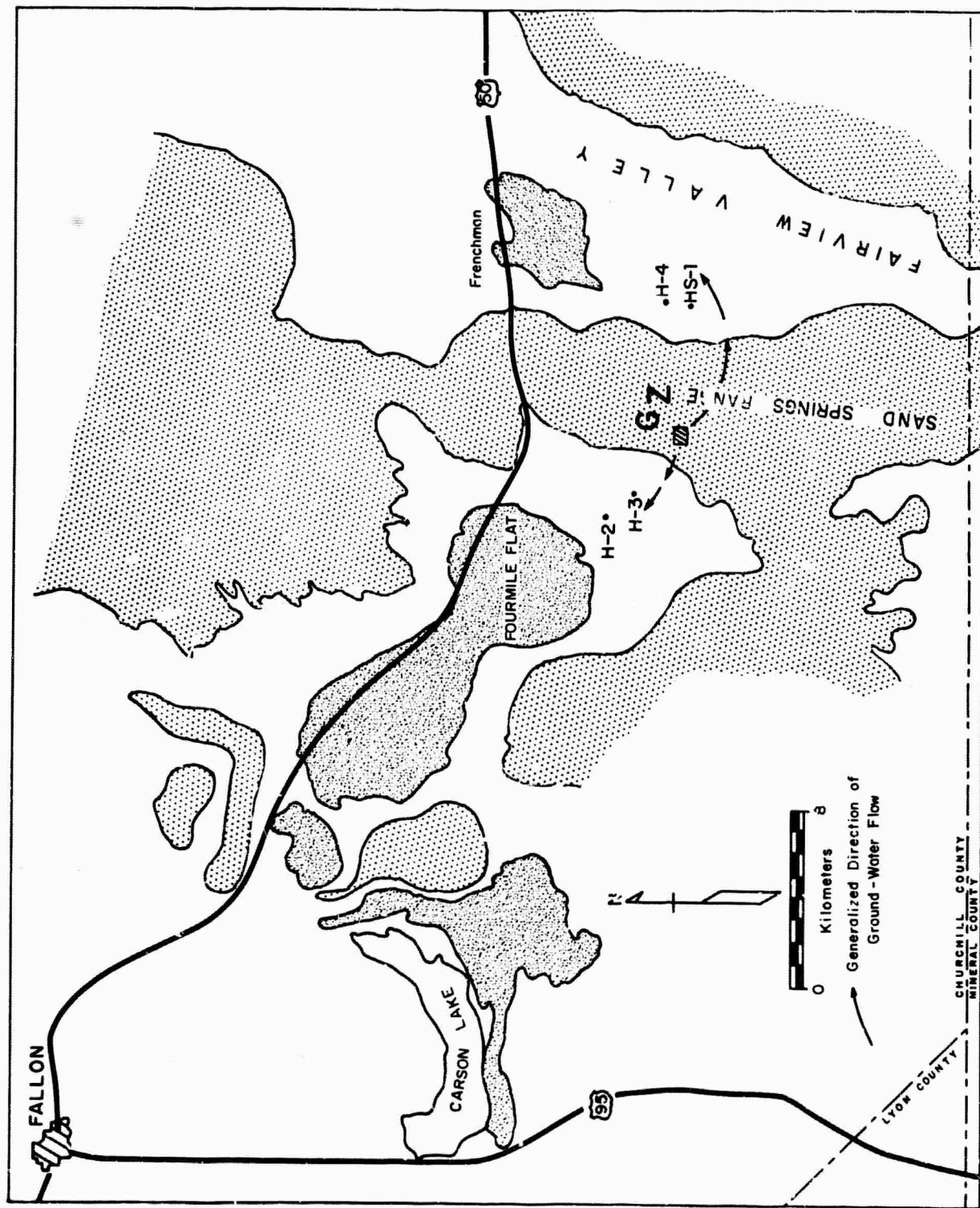


Figure 1. Site of the Shoal Event, Regional Plan View.

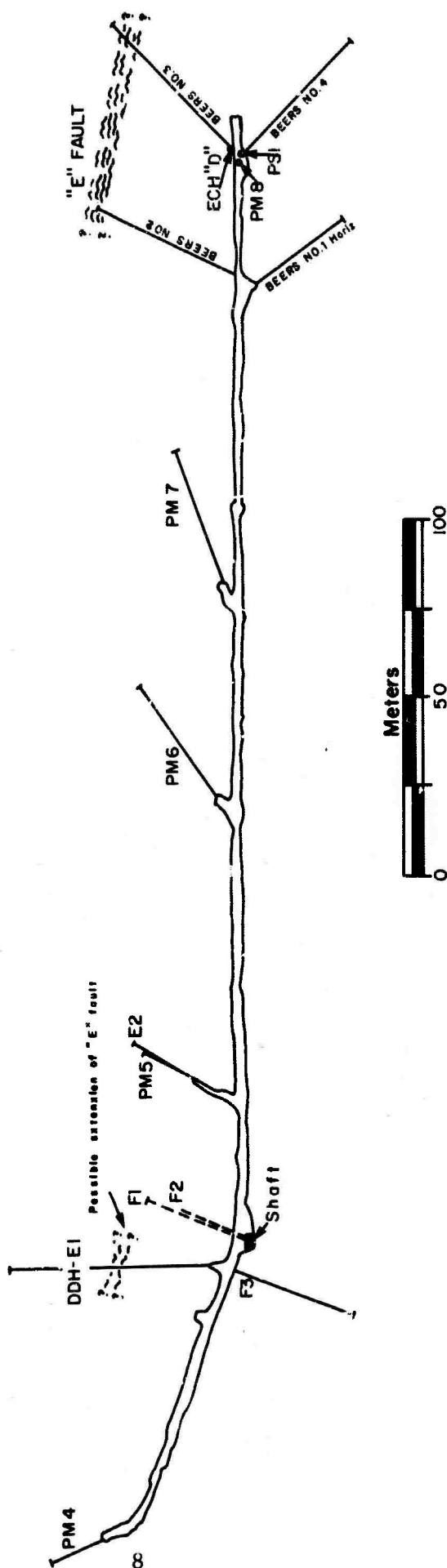
emplacement shaft and drift complex was selected to avoid major geologic structures and construction was estimated to be completed in late July 1963. Difficulties with caving and underground flooding resulted in a delay of the ready date. Holes were drilled at the end of the East Drift (Figure 2) in August 1963 to define the location of faults; these indicated that no major structural zones existed within 30 meters of the shot point. Surface and subsurface drill holes were grouted preparatory to the shot.

The Shoal Event, a 12.5 KT nuclear detonation, one in a series of tests in the Vela Uniform program, occurred at 1000 hours PST on October 26, 1963. The test was conducted in the granite of the Sand Springs Range at a buried depth of 367 meters.

Pre- and post-shot hydrologic and geologic data for the H-NSC program were developed by DRI and NBM, University of Nevada, and were supplemented by data gathered by H-NSC personnel during underground site inspections. Chemical studies of Shoal ground water were conducted at the H-NSC Palo Alto laboratories.

1.3 GEOLOGIC HISTORY

The Shoal Event occurred in a region typical of Basin-Range morphology, consisting of fault-block mountains and alluvial-filled valleys. The Sand Springs Range trends north-south with irregular boundaries defined by high-angle northeast and northwest faults. The Range comprises metamorphosed Paleozoic and Mesozoic marine sediments surrounding a central



FROM: UNIVERSITY OF NEVADA, 1965, PLATE 5

Figure 2. Plan View, Shoal East and West Drift.

granitic intrusive body of Cretaceous age. Tertiary and Quaternary volcanic rocks overlie the crystalline rocks locally and numerous aplite-pegmatite dikes are evident in the western and central part of the Range. The dikes, as well as the granitic and metamorphic rocks, are intruded by younger andesite and rhyolite dikes which typically occupy prominent structural openings. East of the Range, Fairview Valley contains Tertiary and Quaternary alluvial and aeolian sediments as much as 1765 meters thick, based on geophysical surveys. Fourmile Flat is a pediment west of the Sand Springs Range consisting of alluvial fans, pediment sand and gravels, aeolian, and playa deposits underlain by a relatively shallow west-sloping crystalline basement. The unconsolidated deposits thicken westward to about 395 meters.

The deposition of Paleozoic and early Mesozoic marine strata was interrupted by several episodes of folding and thrust faulting. The emplacement of the granitic intrusion in the project area, regional uplift in the latest Mesozoic, volcanism and sedimentation in the middle and late Tertiary, and normal faulting extending into the late Pliocene, formed the gross features of the Range. The present morphology of the region is the consequence of erosion and intermittent uplift of the mountain ranges and alluvial deposition (fluvial, lacustrine, aeolian) in the adjacent valleys during the Pleistocene and Recent.

1.4 STRUCTURAL FEATURES

The active tectonic history of this region is attested to by several prominent structural features. Folding appears mainly in the metamorphic rocks at the south end of the range but is not a prominent feature. However, evidence of intermittent faulting is present both in the high-angle northeast and northwest faults which define the Sand Springs Range boundaries, and in the faults and associated joint patterns which are conspicuous within the range itself. The northwest-trending faults and accompanying parallel joints are quite prominent, and aplite-pegmatite, andesite, and rhyolite dikes are intruded along these breaks. Generally offsetting these faults and associated dikes is a system of northeast-trending faults. The northeast-trending faults, many of which contain gouge and brecciated wall rock, are accompanied by closely-spaced, well-developed parallel fracture cleavage. At the north end of the Range, a thrust fault which dips north cuts the metamorphic rocks, but direction of movement along the thrust is not discernible.

1.5 REGIONAL HYDROLOGY

The alluvial fill in the valleys east and west of the Sand Springs Range contains and transmits appreciable quantities of ground water. Ground water occurs in the granite and other crystalline rocks of the Range; however, the amount is small and its movement is slow.

In Fairview Valley, ground-water movement is toward the north, consistent with surface drainage. In Fourmile Flat, flow is west to northwest, terminating in the center of a closed basin and regional discharge area about ten kilometers west of the Sand Springs Range.

A sub-humid to semi-arid climate prevails in the general project area. Minor precipitation and restricted infiltration into the relatively impermeable crystalline rocks suggest that only minor natural recharge occurs in the Sand Springs Range proper. Recharge to the valley fill sediments is derived from precipitation, intermittent mountain streams that seep into peripheral alluvial fans, and unknown but probably small quantities of ground water flowing laterally out of the crystalline complex.

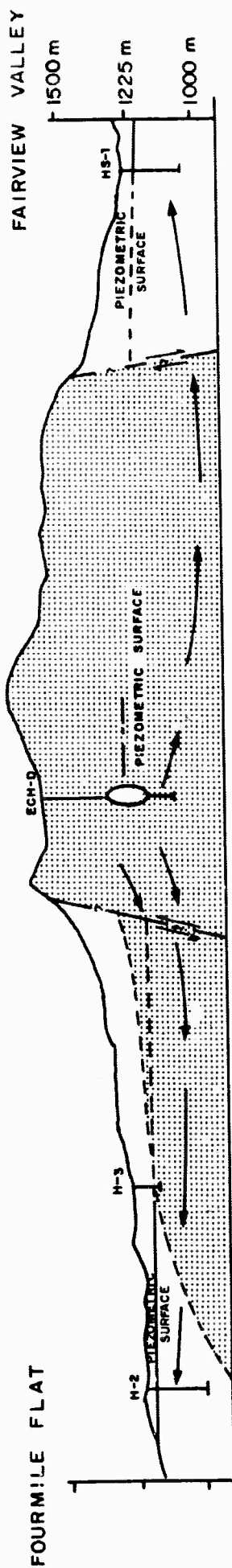
On the basis of data developed by their investigative program, DRI has postulated the existence of a regional ground-water flow system in which mechanical (potential) energy differences supply the driving force to move ground water from recharge areas where water is added to the system to discharge areas where water is lost from the system. Hydrologic relationships indicate that Fairview Valley (and Dixie Valley to the north) and Fourmile Flat act as discharge areas where water is lost principally by evaporation near the ground surface. The Sand Springs Range, probably one of several local recharge areas, contributes a limited amount of water to this system by downward infiltration of precipitation.

Lithologic drilling logs and aquifer hydraulic properties obtained from well discharge tests (University of Nevada, 1965) indicate that confined hydraulic conditions exist in alluvium in both Fairview Valley and Fourmile Flat. Hydraulic potentials in the valleys are consistently lower than those observed in wells in the granite of the Sand Springs Range. Water levels observed in drilling, although not entirely conclusive, suggest a decrease in potential with depth in the saturated granitic rocks of Sand Springs Range. The natural flow pattern, therefore, appears to be downward in the Range with lateral movement of ground water from the saturated crystalline rocks toward the valley fill material in the east- and west-bounding valleys, see Figure 3.

Two pumping tests were conducted in test hole H-2 in Fourmile Flat (Figure 1) in order to determine aquifer properties, but neither test was conclusive. The recovery data from test two (University of Nevada, 1965, Figure 16, p. 79) allow an approximation to be made for the transmissivity coefficient of the valley fill, about 110 square centimeters per second (cm^2/sec).

Hydrologic investigations were conducted in wells HS-1 and H-4 in Fairview Valley (Figure 1) testing two separate confined zones in the alluvium, the upper zone between 94 and 161 meters depth and the lower zone between 174 and 209 meters depth. The transmissivity coefficients derived from these tests were $24.6 \text{ cm}^2/\text{sec}$ and $16 \text{ cm}^2/\text{sec}$ for the upper and lower

SAND SPRINGS RANGE



HORIZONTAL SCALE 1:63,000
VERTICAL SCALE 1:24,000

Figure 3. Vertical Cross-Section, Site of Shoal Event.

zones, respectively, and the storage coefficients of each were about 2×10^{-4} (University of Nevada, 1965, Table 4, p. 75). The specific capacities of wells HS-1 and H-4 were calculated to be 0.37 and 0.5 liter/sec/meter of drawdown, respectively. These values are moderately low for the derived transmissivity and storage coefficients. This could result from incomplete well development or because specific capacities tend to decrease with duration of pumping and thus the values represent end-of-test results. Another possibility is that hydrologic boundary effects may have been realized because of the proximity of the pumping wells to the much less transmissive crystalline rocks of the Sand Springs Range. This would decrease the relative yields from the wells as the end of the testing was approached, and could produce the effect of lowering specific capacity.

The metamorphic and intrusive rocks which comprise the Sand Springs Range have less capacity to transmit water than the adjacent valley fill material. In hydrologic test holes which penetrate one hundred or more meters of the saturated granite of the range, low (0.3 liter/sec) pumping rates rapidly depressed water levels attesting to the low transmissive capacity of the fractured rock. Bailer tests were conducted in several wells in the granite (ECH-D, PM-1, PM-2, PM-3, PM-8, and USBM-TH-1; Figure 4). Recovery curves derived from these tests ranged from very complex to inconclusive with respect to determination of a representative transmissivity coefficient (T) for the fractured granite aquifer. Well H-3

on the west slope of the Sand Springs Range, which penetrated granite below a veneer of alluvium, also was tested. A credible range of values for the coefficient of transmissivity in the granite, based upon these tests, is $0.02 - 0.2 \text{ cm}^2/\text{sec}$. Assuming the thickness of the more prolific saturated fractured aquifer penetrated by well ECH-D, about 200 meters, is representative of the granite aquifer, then, dividing into the above transmissivity coefficients, the apparent hydraulic conductivity of the granite ranges from 10^{-6} to 10^{-5} cm/sec .

The hydraulic gradient in the alluvium of Fairview Valley between well HS-1 and Frenchman Station, about 4.75 kilometers north of HS-1 (see Figure 1), is $I = 0.00057$. The apparent hydraulic conductivity, K' , is about $3.7 \times 10^{-3} \text{ cm/sec}$. Though no reliable value of effective porosity, p , is known, it probably ranges from 10 to 20 per cent. Therefore, the average interstitial pore velocity (\bar{v}) of ground water in Fairview Valley alluvium, from the equation

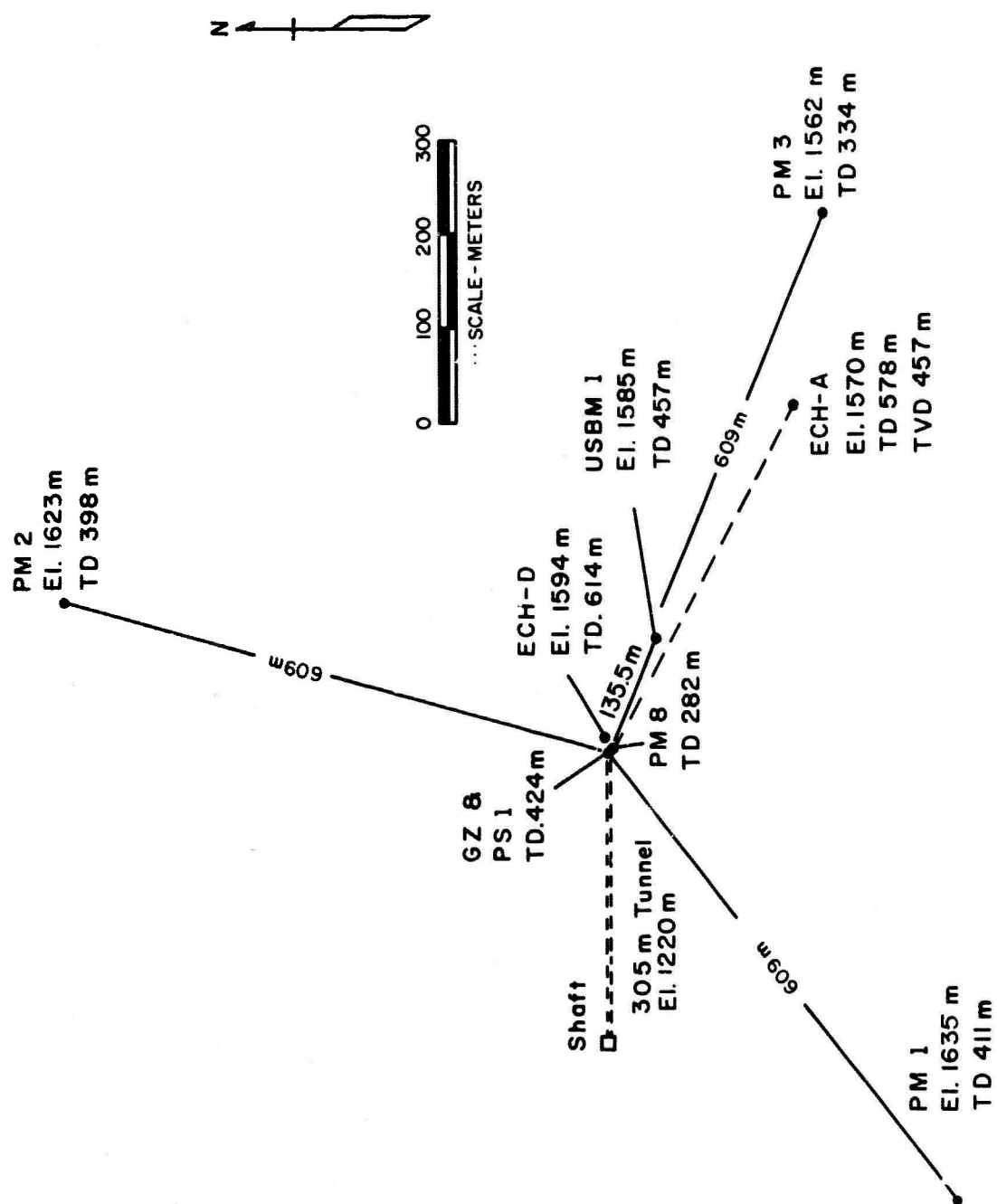
$$\bar{v} = \frac{K' I}{p}$$

and substituting, is

$$\bar{v} = \frac{3.7 \times 10^{-3} \times 0.00057}{0.10} = 2.1 \times 10^{-5} \text{ cm/sec}.$$

For an estimated $p = 20$ per cent, $\bar{v} = 1.1 \times 10^{-5} \text{ cm/sec}$.

In Fourmile Flat, the hydraulic gradient, I , is about 0.00028, the apparent hydraulic conductivity, K' , is estimated to be about $5.6 \times 10^{-3} \text{ cm/sec}$ and the porosity, p , is between 10 and 25 per cent. The average



from: Atkinson, C. H. 1964
Figure 3.1, p. 14

Figure 4. Drill Hole Locations, Shoal Test Site.

interstitial pore velocity of ground-water movement in Fourmile Flat sediments is

$$\bar{v} = \frac{5.6 \times 10^{-3} \times 0.00028}{0.10} = 1.6 \times 10^{-5} \text{ cm/sec}$$

and for an estimated 25 per cent porosity, $\bar{v} = 6.2 \times 10^{-6} \text{ cm/sec}$.

It is not possible to compute with similar assurance the rate of ground-water movement in the crystalline complex which comprises the Sand Springs Range. The apparent hydraulic conductivity has been approximated, but the hydraulic gradient in these rocks is uncertain and the effective porosity of fractures and joints may be only crudely estimated. On the basis of available information, the rate of movement is considered to be extremely low. The problem of ground-water flow velocities in the crystalline complex is further considered in Section 2.4 in connection with estimates of nuclide transport by ground water.

1.6 SITE HYDROLOGY

The Shoal emplacement workings and underground drill holes intersected numerous joints, fracture cleavages and faults in the granite. Below about 325 meters in the workings (elevation ~ 1290 meters) many of these structural features were saturated and supported a small inflow of water, in most cases less than 0.6 to 1 liter/sec. Flow decreased rapidly with time, and several weeks prior to detonation, with one or two minor exceptions, inflow from individual points had diminished to minor seepage

or ceased completely. During the final stages of underground construction, four horizontal fault-definition holes (B-1 through B-4, Figure 2) explored the granite for about 30 meters around the working point (WP), but little water was produced and flow had ceased prior to detonation. Just prior to detonation, pumps were producing about 0.3 liter/sec from the shaft sump (R. J. Burton, Sandia Corporation, oral communication to J. V. A. Sharp, H-NSC). All drill holes had been grouted at this time and this flow was seepage across the granite-drift interface.

Diamond drill hole-E1 (DDH-E1) produced a substantial continuous flow of water for two months from a zone somewhat over 30 meters north of the west drift (Figure 2). Flow commenced at about 13 liters/sec and had declined to about 4 liters/sec at the time of grouting of the drill hole prior to the detonation. Flow from DDH-E1 was responsible for most of the water pumped from the shaft-drift complex during the underground operation. The mode of occurrence of this water is not clear, but may be related to a possible underground extension of the west to northwest-trending "E" fault (Figure 2). No natural large-scale communication exists between this water zone and the underground workings.

Observations in connection with the underground operation permit several important generalizations. One, the water at depth in the granite occurs in structural openings. Two, the inability of most of the structural openings to sustain a continuous flow indicates that water movement in the

mass of granite is quite restricted. Initial "flush" production in part may have resulted from disturbances to the granite during mining and drilling operations. Three, zones exist which contain large quantities of water and along which relatively unrestricted water movement may occur. The amount of water produced by DDH-E1, on the order of 4×10^7 liters prior to grouting, provides a rough measure of the possible relative importance of such zones to the occurrence and movement of water.

Data on the water level in the granite near ground-zero have been obtained for six drill holes (PM-1 through PM-3, PM-8, ECH-D, USBM hole; Figure 3) and the emplacement shaft. Observed levels fall within a 165-meter interval, about 1235 to 1400 meters elevation, and include variations both between and within individual holes. Water level declines were noted subsequent to hydrologic bailing tests and further drilling and deepening of holes. Potentials commonly decrease with depth in recharge areas and the decline of water levels observed during drilling may possibly reflect adjustment of the water column to lower hydraulic potentials at depth. This is evidence for downward component of ground-water flow. In at least several instances, drilling and testing activities are believed to have influenced adversely the validity of the measured levels, and may account to an unknown degree for variations in water level between and within holes.

Coefficients of transmissivity (T) for the fractured granite were computed by H-NSC using the Jacob modified nonequilibrium method and

late data derived in controlled bailer recovery tests on PM-1 and PM-3 (University of Nevada, 1963, pp. 16-26). Apparent hydraulic conductivities (K') based upon estimated thickness of saturated rock are

$T = 0.11 \text{ cm}^2/\text{sec}$ and $K' = 1.4 \times 10^{-5} \text{ cm/sec}$ for PM-1,
and, $T = 0.025 \text{ cm}^2/\text{sec}$ and $K' = 1.7 \times 10^{-5} \text{ cm/sec}$ for PM-3.

To test the validity of the hydraulic properties derived above, an analysis of observed average water inflow to the shaft-drift complex was made, using the Dupuit Equation,

$$\frac{Q}{L} = \frac{K'}{2x} (h^2 - h_0^2)$$

where Q = average inflow rate to the drift from all sides (not including inflow from DDH-E1), 0.3 liter/sec or about $300 \text{ cm}^3/\text{sec}$;

K' = apparent hydraulic conductivity of the granite in cm/sec;

x = distance from drift, perpendicular to it, wherein water levels are influenced by drainage to the linear sink, assumed here to be $5 \times 10^4 \text{ cm}$;

L = length of drift = $4 \times 10^4 \text{ cm}$;

h_0 = water level above base of drift at the drift, assumed to be zero centimeters; and

h = water level above base of drift elevation at distance x , $8.5 \times 10^3 \text{ cm}$.

Substituting and rearranging terms,

$$K' = \frac{300 \text{ cm}^3/\text{sec} \times 2 (5 \times 10^4)}{4 \times 10^4 \times (-8.5 \times 10^3)^2}$$

$$= 10^{-5} \text{ cm/sec,}$$

very closely approximating the upper limit of apparent hydraulic conductivity derived in Section 1.5 and above.

Because of the apparent consistency of values derived in the above analyses, the value, $K' = 10^{-5}$ cm/sec, will be used as an average hydraulic conductivity for the mass of the granite. This is in good agreement with values projected from analyses of well-yield and water-injection data for several crystalline rocks (Davis, S. N. 1963, p. 24). Higher conductivity values indicated in the early recovery portion of the test on PM-3 may be associated with a highly fractured zone at the bottom of the hole. The water-bearing zone in DDH-E1 could have a conductivity as much as four or five orders of magnitude greater than that of the mass of the granite or on the order of 10^{-1} to 1 cm/sec.

Chapter 2

CONTAMINATION OF GROUND WATER

2.1 EXPLOSION EFFECTS

Calculations are based upon a 12.5 kiloton device at Shoal, forecasting a cavity radius of about 24.4 meters and a chimney height above the shot point of about 110 meters. Hydyme results and other data indicate that the Shoal device detonated as predicted (U. S. Atomic Energy Commission, 1964, p. 81).

Geophysical logging of the post-shot re-entry hole (PS #1; Figure 3) indicates the following: (1) The top of the Shoal chimney is characterized by a void eleven meters high, the roof of the void located 108.5 meters above the shot point at an elevation of 1342.5 meters above mean sea level (m/msl); (2) the bulk of the explosion melt, about ten meters thick, is located at the base of the chimney (elevation 1208 m/msl); and, (3) the cavity radius, R_c , is about 26 meters.

Apparently undisturbed granite was encountered at a drilling depth of 408 meters (1193 m/msl), implying a fracture radius from the working point of about 41 meters. However, USBM drill hole No. 1, 135.5 meters to the southeast of GZ (Figure 4), was completely offset at a depth of 345 meters, suggesting that lateral shock-induced fractures extend a minimum distance of 5.2 times the radius of the cavity (Atkinson, C. H., 1964, pp. 19 and 29).

Small amounts of radioactivity were found in the air below a plug at 125 meters depth in the USBM drill hole. A 1.7×10^7 cubic centimeter air sample that was passed through cryogenic filters during post-shot cleanout (Atkinson, C. H., 1964, p. 26) contained 7.99×10^{-4} μC Xe^{133} , 2.21×10^{-4} μC I^{131} , and a trace of Cs^{137} . The inference from these data is that the radioactive fracturing radius is at least 135.5 meters (5.2 times the cavity radius). However, the radius of radioactive fracturing determined from one reference point is not conclusive. The explosion-distribution of radionuclides into the geologic medium may have been non-spherical and the single reference point at USBM No. 1 may not be representative of the average radioactive fracturing radius. From empirical results in tests in various media at the Nevada Test Site, the radioactive fracturing radius, R_{rf} , and maximum fracturing radius, R_{mf} , determined by R. F. Beers, Inc., are $R_{rf} = 2.95 R_c$, and $R_{mf} = 4.35 R_c$, which for Shoal predicts $R_{rf} = 77$ meters, and $R_{mf} = 113$ meters (see Figure 5). This is somewhat less than fracturing and associated radioactivity observed in the USBM hole.

2.2 EXPLOSION - PRODUCTION AND DISTRIBUTION OF RADIONUCLIDES

An estimation of the quantities and identity of the radionuclides produced in the Shoal detonation requires consideration of the total yield, external neutron fluxes, and the type of chemical elements exposed to these fluxes.

Calculations for radionuclide production at Shoal are based on information and assumptions as follows:

- 1) The Shoal device had a fission yield of 12.5 KT.
- 2) Fission yields appropriate to "fission-spectrum" neutrons with U^{235} were used for calculation of fission product levels (Carnahan, C. L., October 9, 1964).
- 3) Effects due to activation of device materials and neutron-moderating and absorbing materials around the device (other than the geologic medium) were not considered.
- 4) Neutron-activation production estimates are based on x-ray spectrographic analyses of 34 rock samples from drill hole ECH-D (University of Nevada, 1965, pp. 203-237). Calculation procedures for activation in average earth's crust (Carnahan, C. L., 1964, HNS-1229-54) were employed with adjustments for differences in abundances of elemental reactants between the average crust and the Sand Springs Range granite.
- 5) Tritium is produced by neutron activation of lithium⁶ by the reaction $Li^6 (n, \alpha) H^3$. For a conservative safety evaluation of tritium in ground water, a lithium concentration in the Shoal granite equal to ten times the NBM number (about 25 ppm) (University of Nevada, 1965, p. 224) was chosen, that is, about 250 ppm lithium, for purposes of estimating tritium production by activation.

TABLE 1. RADIONUCLIDE PRODUCTION FROM AN ASSUMED 12.5 KT
SHOAL DEVICE

Nuclide	Half-Life in years	Source*	Shot-Time Activity in curies
Ce ¹⁴⁴	0.78	f	6.7×10^4
H ³	12.3	a	3.0×10^4
Pm ¹⁴⁷	2.7	f	9.7×10^3
Ru ¹⁰⁶	1.0	f	6.4×10^3
Cs ¹³⁷	30.0	f	2.2×10^3
Fe ⁵⁵	2.6	f	2.0×10^3
Sr ⁹⁰	28.0	f	1.9×10^3
Sb ¹²⁵	2.7	f	8.0×10^2
Eu ¹⁵⁵	1.7	f & a	4.7×10^2
Sm ¹⁵¹	90.0	a & f	4.2×10^2
Cd ^{113m}	14.0	f	3.0×10^1
Gd ¹⁵³	0.6	a	1.5×10^1

*f = fission product

a = activation product

NOTE: Table 1 includes device and neutron-activation produced non-gaseous radionuclides in quantity greater than 10^1 curies and with half-lives greater than one-half year. The amount of fission-produced tritium is small relative to the total neutron activation

production of tritium and does not alter the above figure significantly.

2.3 ENTRY OF RADIONUCLIDES INTO GROUND WATER

Aqueous concentrations of radionuclides in the Shoal explosion zone waters are estimated below.

Tritium

The following conditions and assumptions are used:

- 1) 3.0×10^4 curies of tritium were produced primarily by neutron activation of the surrounding granite (Table 1, Section 2.2).
- 2) Tritium is not preferentially sorbed on geologic materials relative to ground water, and
- 3) Tritium is chemically combined as water and uniformly mixed in about 4.15×10^{10} ml of water upon infill of the rubble chimney to the water-table level.

Correcting for radioactive decay during a ten-year rubble chimney infill, the average concentration in the chimney as near stable aquifer conditions are approached will be

$$C_{aq}^{H^3} = 4 \times 10^{-1} \mu\text{c/ml.}$$

Sr⁹⁰, Cs¹³⁷

The following conditions and assumptions are used:

- 1) 90 per cent of the Sr⁹⁰ and Cs¹³⁷ produced by the explosion escaped incorporation in the melt, and, subsequent to infill, will be distributed evenly throughout the rubble chimney,

2) 2.2×10^3 curies of Cs^{137} and 1.9×10^3 curies of Sr^{90} were produced by the explosion (Section 2.2), and

3) Chemical distribution coefficients (K_d) for strontium and cesium between Shoal granitic chimney rubble and Shoal water have not been measured, but data in the literature suggest that a value of $K_d = 10 \text{ ml/g}$ is reasonable.

The resulting average concentrations in the rubble chimney, according to

$$C_{\text{aq}}^{\text{rn}} = \frac{A(\text{uc})}{K_d M_r(\text{g}) V_{\text{aq}}(\text{ml})},$$

and taking into account decay during chimney infill, are

$$C_{\text{aq}}^{\text{Sr}^{90}} = 2 \times 10^{-4} \text{ uc/ml.}$$

$$C_{\text{aq}}^{\text{Cs}^{137}} = 3 \times 10^{-4} \text{ uc/ml.}$$

Other Radionuclides

The remaining nuclides listed in Table 1 are either incorporated in the relatively insoluble melt and unavailable to ground water or are of sufficiently short half-life to decay to negligible levels prior to complete infill of the chimney. These nuclides will not be considered further.

Radiologic assay of a water sample taken in PS #1 in the lower rubble chimney on January 18, 1965, shows concentrations of Sr^{90} , Cs^{137} , and H^3 to be somewhat lower than the anticipated concentrations given above.

The assayed concentrations are even lower considering the incomplete time and degree of infill at the time the sample was taken. However, neither this sample nor another similar sample taken on June 28, 1965, appear to represent true rubble chimney ground water, but are, most likely, slightly contaminated condensate waters in a partially-plugged casing (see Section 3.2). This factor alone could account for the low concentrations revealed by the analyses.

Present and future concentrations of nuclides in chimney waters may diverge from the expected concentrations at completion of infill because of several factors. The assumed distribution coefficients may be incorrect by a factor of five or so; the chemical sorption equilibria are influenced by factors of ground-water chemistry and surface area and mineralogy of the granite adsorbent. Evaluation of these factors is not possible with the data at hand. The assumed uniform explosion distribution and spatial mixing of radionuclides in the rubble chimney are unlikely. Rather, some data from shots at the Nevada Test Site indicate a non-uniform distribution of radioactivity in the rubble chimney, suggesting that aqueous concentrations will be high in the lower chimney and low in the upper chimney, relative to the estimated average; i.e., well-mixed, concentration.

In the interest of uncompromised hydrologic safety, the calculated concentrations for H^3 , Sr^{90} , and Cs^{137} for further discussion will be

increased by a factor of five to take into account the uncertainties expressed above. These values are conservative yet credible upper concentration limits for these hazardous radionuclides.

2.4 TRANSPORT OF RADIONUCLIDES BY MIGRATING GROUND WATER

A depressed zone of no-water was created in the Sand Springs Range granite aquifer by: (1) Removal of water which seeped into the Shoal underground workings during construction; (2) possibly by the evacuation of ground water surrounding the point of detonation due to the high pressures created by the blast; and (3) creation of new unsaturated pore space of the explosion cavity-collapse chimney. This dewatered region is not in equilibrium with the ambient hydraulic potential field. The aquifer will respond by striving toward a stabilized state, and ground water will flow inward toward the hydraulic potential sink of the dewatered zone.

Radionuclides in solution may migrate beyond the limits of the rubble chimney through molecular diffusion during the aquifer adjustment stage. However, large-scale transport of radiocontaminated ground water will not occur until the water in the underground workings and rubble chimney is in or near equilibrium with the surrounding environment. One may reasonably assume that the equilibrium water level will very nearly approach the pre-Shoal potentiometric surface.

In order to estimate a probable rubble chimney fill-up rate and total fill-up period, it is necessary to take the following approximations and assumptions into consideration:

1) The underground workings (east and west drifts and lower part of the shaft) are located on a lower horizon than much of the rubble chimney and will consequently fill with in-flowing ground water before the bulk of the chimney. The drift complex has an approximate volume of 2200 cubic meters (366 m. long x 6 m.² drift cross section). The total length is 396 meters for both east and west drifts; however, about 30 meters of this length is incorporated into the rubble chimney as a result of the detonation.

2) The void space to be filled with ground water increases upwards in the rubble chimney as a result of lesser compaction by overlying collapse materials. In addition, the in-fill or recovery rate is not constant. As the chimney fills, hydraulic head differences will decrease, bringing about a decrease in recovery rate. However, the decreasing rate is uniform with respect to time.

3) The lower part of the rubble chimney and the underground workings fill with ground water simultaneously. Initial infill is relatively rapid due to the presumably steep hydraulic gradient between the base of the chimney and the more or less stable water level in the granite at some distance away from GZ, and in part as a result of the comparatively smaller volume of pore space to be filled in the lower chimney.

4) The undisturbed granite medium hydraulically connected with the rubble chimney is more or less uniformly fractured and the fractures are

evenly distributed, thereby approaching homogeneity. The apparently slow water level recovery rates observed in post-shot investigations suggest that neither an extension of the water-bearing zone tapped by DDH-E1 nor a similar zone was breached as a result of the detonation. The response of such an aquifer is very similar to a porous medium where large volumes of water-bearing rock are involved.

The fractures are oriented NE-SW and NW-SE, whereas local-regional ground-water gradients are E-W. Most of the fractures are steeply dipping to vertical and observed water levels indicate that potential values decrease with depth. Taken together, these controls could easily result in gross isotropic flow.

5) The essentially uniform fracture network implies uniform and constant permeability and transmissivity.

6) The granite body is of sufficient areal extent to be considered hydraulically infinite.

7) The Shoal rubble chimney probably does not fully penetrate the aquifer; however, the total saturated thickness of the aquifer is unknown. It is probable that the total saturated thickness is less than a magnitude greater than the chimney height. Distortion of flow paths at the bottom of the chimney would be minor due to slow flow rate.

8) The rubble chimney-drift complex is essentially a localized sink and flow to it would be radial. Gross fracture flow is governed by the smallest of the interconnected fractures, resulting in laminar flow.

Assuming an initial inflow rate in the granite of $Q = 300 \text{ cm}^3/\text{sec}$ which is about the same as the last recorded inflow rate prior to the detonation (see Section 1.5), the fill-up time in the drift complex is about 80 to 100 days. Though infill will be relatively rapid in the lower chimney (item 3), the rate of infill will decrease with time (item 2). Calculations indicate that total rubble chimney fill-up may take on the order of 10 years.

When aquifer restabilization is approached, essentially natural ground-water conditions should prevail, and flow will again be downward and outward from the central part of the Sand Springs Range. There will be convergence of flow toward the more permeable rubble chimney inclusion in the more or less uniform granite aquifer, and divergence of flow down gradient away from the chimney. The flow rate of radiocontaminants in ground water away from the chimney will be governed, however, by the hydraulic and chemical-exchange properties of the undisturbed granite.

Extremely low ground-water velocities exist in the granite aquifer based upon available hydrologic test data (see Section 1.5). An approximation of the rate of movement may be derived from several already suggested values, and substitution of these values in the velocity equation:

$$\bar{v} = \frac{K' I}{P}$$

where: K' = apparent hydraulic conductivity = 10^{-5} cm/sec (Section 1.5);
 I = hydraulic gradient 0.015 (Nevada Bureau of Mines, Report 2, Part 2, 1963, p. 29); p = porosity of the fractured granite, estimated = 0.1 to 1.0 per cent; and the resulting possible average ground-water velocity in the granite, \bar{v} , is 1.6×10^{-6} to 1.6×10^{-5} cm/sec.

The cross-cutting fracture network of the aquifer precludes the possibility of straight-line flow of ground water. More likely, a tortuous, circuitous path will be taken in a general down-gradient direction. However, this retarding, long-path may be compensated for by interconnection locally with high permeability and consequently possible high velocity fractures such as the one penetrated by DDH-E1. The possibility that any one of these high permeability fractures extends uninterrupted for the entire breadth of the Sand Springs Range is extremely remote. Any such feature would probably either pinch out, be offset by another less permeable fracture, or be truncated by one or more low permeability intersecting fractures.

The fracture network and location of possible high velocity flow fractures is too complex for a detailed flow analysis of the granite aquifer. It is believed that the interconnection with any high velocity feature(s) is compensated for by the circuitous path which the ground water must flow. It is reasonable to conclude, therefore, that straight-line flow with average pore velocities of 1.6×10^{-6} to 1.6×10^{-5} cm/sec closely approximates the

transmission of ground water through the granite. With these velocities, flow along even the most direct path to the alluvium, for example, to the vicinity of H-3 and H-2 on the west side of the Sand Springs Range (Figure 1), a distance of about 4500 meters, would take a minimum of nine hundred and a maximum of nine thousand years.

The potentiometric gradient in the granite and fracture frequency, however, raise the strong possibility of a south easterly flow toward Fairview Valley (University of Nevada, 1965, p. 301). Flow in this direction would take an even longer period to leave the granite system.

GROUND-WATER SAFETY ANALYSIS AND DISCUSSION

3.1 RADIOCONTAMINATION HAZARD

The conservative, credible limiting* concentrations of Sr^{90} , Cs^{137} , and H^3 upon infill of the rubble chimney (Section 2.3) exceed by orders of magnitude the maximum permissible concentration for radioactivity in effluents released to uncontrolled areas for average exposure of an exposed population group (AEC Manual, Chapter 0524, Standards for Radiation Protection, Annex 1, Table II) (Table 2).

TABLE 2. LIMITING AQUEOUS CONCENTRATIONS OF NUCLIDES AND ACCEPTABLE LEVELS.

Nuclide	Limiting Concentration in Rubble Chimney Water at Infill, $\mu\text{c}/\text{ml}$	Acceptable Concentration, Chapter 0524, $\mu\text{c}/\text{ml}$	Factor Exceeding Acceptable Concentration
Sr^{90}	1×10^{-3}	1×10^{-7}	1×10^4
Cs^{137}	1.5×10^{-3}	7×10^{-6}	2×10^2
H^3	2×10^0	1×10^{-3}	2×10^3

However, the rate of ground-water migration in the granite is low (average 50 to 500 cm/year; Section 2.4) and nuclide concentrations greater than

*Estimated average concentrations (Section 2.3) increased by factor of five.

acceptable levels will be confined to the vicinity of the explosion zone, even taking into account the possibility of initial explosion distribution of nuclides along fractures, one hundred meters or more into the geologic medium (Section 2.1). Tritium transported as tritiated water is not retarded by chemical interaction with the geologic medium and it is considered very unlikely that greater-than-acceptable concentrations will extend more than one thousand meters from the explosion zone prior to radioactive decay and dilution by mixing (dispersion) to acceptable concentrations. Transport of Sr^{90} and Cs^{137} will be retarded by chemical interaction with the granite and the aqueous transport of these nuclides will be even more restricted than in the case of tritium.

Consideration of the transport distance to the nearest ground-water use point, on the order of 5000 meters or more, relatively slow ground-water movement, radioactive decay of nuclides, retardation by the geologic media in the case of Sr^{90} and Cs^{137} , and dilution by mixing with uncontaminated water (dispersion) suggests that negligible radiocontamination hazard to regional ground-water supplies will arise from the Shoal Event.

3.2 POST-SHOT GROUND WATER MONITORING

The Shoal re-entry drill hole, PS #1, was completed as a hydrologic observation well for site-safety and long-range ground-water safety programs, particularly to monitor rubble-chimney fill-up and radionuclide concentrations in ground water (U. S. Atomic Energy Commission, 1964,

p. 47). This program includes the periodic measurement of recovery water levels in the post-shot hole and the collection of water samples for radiologic and chemical assay.

The original Shoal post-shot hole use criteria, suggested by H-NSC in December, 1963 (L. B. Werner, December 23, 1963), and confirmed in January, 1964 (NVOO, January 23, 1964), for immediate and future post-shot studies included measurement of infill water levels and collection of water samples on a monthly or otherwise appropriate basis for a period of five years.

During gamma-ray logging on January 16, 1964, a constriction in the casing was noted at a depth of about 396 meters, (1198 m/msl elevation), and water-sampling tools could not be lowered beyond the constriction. On February 27, 1964, DRI and the U. S. Public Health Service attempted to re-enter PS #1, collect water samples, and measure temperatures at various elevations in the hole. The temperature and sampling instruments could not be lowered below 377 meters (1217 m/msl elevation) where an apparent obstruction was located (Maxey, G. B., March 2, 1964). The sampling bailers in the February 27 re-entry were consistently damp and contained some water and sludge (about 0.5 liter). No temperatures as high as 428° F. were measured (the lower limit of the functioning sensor). The existence of a standing water level in the rubble chimney could not be established by results of the February 27, 1964, re-entry.

The constricted casing and obstruction in PS #1, effectively isolating the lower portion of the hole from sampling efforts, and the lack of obvious infill ground water indicated that, for the time being, semi-annual re-entry and sampling of PS #1 would be sufficient for hydrologic safety purposes. Two water samples were collected in 1965, one on January 18 and the other on June 28. Radiologic assay of these samples was made at the H-NSC laboratories in Palo Alto. A total of about 0.5 liter was collected in January, 1965. The presence of sludge and the difficulty encountered in collection of the relatively small amount of water suggests that the sample is probably water of condensation (Mifflin, M., January 26, 1965). Based on temperature sensitive paint samples, the bottom hole (377 meters depth) temperature was probably less than 200° F. However, the January 1965 sampling indicated that more moisture was in the re-entry hole than in earlier attempts, suggesting that either more ground water was reaching the lower chimney zone or that moisture condensation rate had increased, perhaps the result of general lower temperatures (Mifflin, M., January 26, 1965).

A 0.5 liter sample was taken from PS #1 on June 28, 1965. A possible water level was detected by an electrical tape at 369 \pm 2 meters elevation (Mifflin M., June 30, 1965). Chemical analysis of this water by H-NSC showed both low total dissolved content and ionic imbalances relative to the environmental ground water, suggesting again that the recovered water is condensate.

CONCLUSIONS AND RECOMMENDATIONS

The following summarizes those aspects of geologic, hydrologic, and radiologic investigations considered pertinent to the Shoal hydrologic safety evaluation:

- 1) The Shoal Event occurred in the saturated granite of Sand Springs Range, Nevada, wherein ground-water movement is extremely slow,
- 2) Significant quantities of radionuclides were produced by the 12.5 KT detonation and hazardous quantities are expected in ground water in the explosion zone; however, these radionuclides are not free to migrate outward from the explosion zone until the hydrologic system returns to a more stable condition; that is, at least until the rubble chimney fills with ground water,
- 3) Rubble chimney infill to date is apparently very small and anticipated total fill-up and granite aquifer restabilization is not expected for at least D plus 10 years,
- 4) With stabilization achieved, the transport of radionuclides by ground water will be quite slow and radioactive decay and other factors will lower concentrations of nuclides to non-hazardous levels before the migrating radiocontaminated ground water travels more than one thousand meters from the detonation area, and

5) Contamination of ground water by the Shoal Event offers negligible hazard to regional ground-water supplies.

The on-site post-shot ground-water monitoring program has not as yet provided any conclusive evidence of rubble-chimney in-fill. Water samples taken in PS #1 on two occasions and analyzed by H-NSC reveal concentrations of radionuclides below calculated anticipated levels and suggest that these were not ground-water samples, but rather contaminated water of condensation. However, these samples do show concentrations of several radionuclides somewhat above acceptable levels (AEC Manual, Chapter 0524).

With respect to future sampling and post-shot investigations, the following recommendations are made:

1) Re-entry of the post-shot hole should be made on an annual basis for three years to monitor infil' levels, make down-hole temperature measurements, and collect water samples for chemical and radiologic assay.

2) At D plus five years or when rubble-chimney infill is nearing completion, whichever is earlier, the monitoring requirements for maintenance of site hydrologic safety should be re-examined, with the possibility of:

- a) Abandonment of further rubble chimney re-entry,
- b) Continuation of rubble-chimney re-entry program, and

c) Expansion of the monitoring program to include surveillance of water, down hydraulic potential gradient.

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TECHNICAL REPORTS SCHEDULED FOR ISSUANCE BY AGENCIES PARTICIPATING IN
PROJECT SHOAL

AEC REPORTS

<u>Agency</u>	<u>Report No.</u>	<u>Project No.</u>	<u>Subject or Title</u>
NBM	VUF-1001	33.2	Geological, Geophysical and Hydrological Investigations of the Sand Springs Range, Fairview Valley and Fourmile Flat, Churchill County, Nevada
SC	VUF-1002	40.5	Seismic Measurements at Sandia Stations
SC	VUF-1003	40.3	Hydrodynamic Yield Measurements
SC	VUF-1004	45.5	Device Support, Arming, Stemming and Yield Determination
SC	VUF-1005	45.6	Radiological Safety
EC&G	VUF-1006	60.4	Final Timing and Firing Report - Final Photo Report
USBM-PRC	*		Subsurface Fracturing From Shoal Nuclear Detonation
USWB	VUF-1008		Weather and Surface Radiation Prediction
USPHS	VUF-1009		Off-Site Surveillance
USEM	VUF-1010		Structural Survey of Private Mining Properties
USC&GS	VUF-1011		Seismic Safety Net
REEC	VUF-1012		On-Site Health and Safety Report

<u>Agency</u>	<u>Report No.</u>	<u>Project No.</u>	<u>Subject or Title</u>
KFB, Inc.	VUF-1013		Analysis of Shoal Data on Ground Motion and Containment
H-NSC	VUF-1014		Shoal Post-Shot Hydrologic Safety Report
H&N	VUF-1015		Pre-Shot and Post-Shot Structure Survey
H&N	VUF-1016		Test of Dribble-Type Structures
FAA	VUF-1017		Federal Aviation Agency Airspace Advisory
<u>DOD REPORTS</u>			
SC	VUF-2001	1.1	Free Field Earth Motions and Spalling Measurements in Granite
SC	VUF-2002	1.2	Surface Motion Measurements Near Surface
** USC&GS	VUF-2300	1.4	Strong Motion Seismic Measurements
LPI	VUF-2600	1.6	In-Situ Stress in Granite
WES	VUF-2700	9.1	Grouting Support
** STL	VUF-2400	1.7	Shock Spectrum Measurements
SRI	VUF-3001	7.5	Investigation of Visual and Photographic On-Site Techniques
SRI	VUF-3002	7.6	Local Seismic Monitoring - Vela CLOUD GAP Program

TI	VUF-3003	7.8	Surface and Subsurface Radiation Studies
USGS	VUF-3004	7.9	Physical and Chemical Effects of the Shoal Event
ITEK	VUF-3005	7.10	Airborne Spectral Reconnaissance
BR Ltd.	VUF-3006	7.15	The Mercury Method of Identification and Location of Underground Nuclear Sites
NRDL	VUF-3007	7.16	Multi-Sensor Aerial Reconnaissance of an Underground Nuclear Detonation
GIMRADA	VUF-3008	7.17	Stereophotogrammetric Techniques for On-Site Inspection
ISOTOPES	VUF-3009	7.19	Detection in Surface Air of Gaseous Radionuclides from the Shoal Underground Detonation
*** USC&GS		8.1	Microearthquake Monitoring at the Shoal Site
**** GEO-TECH		8.4	Long-Range Seismic Measurements

* This is a Technical Report to be issued as PNE-3001 which will receive TID-4500 category UC-35 Distribution "Nuclear Explosions-Peaceful Applications"

** Project Shoal results are combined with other events, therefore, this report will not be printed or distributed by DTIC

*** Report dated March 1964 has been published and distributed by USC&GS

**** Report dated December 9, 1963, DATDC Report 92, has been published and distributed by UED

LIST OF ABBREVIATIONS FOR TECHNICAL AGENCIES

BR Ltd.	Barringer Research Limited Rexdale, Ontario, Canada
EG&G	Edgerton, Germeshausen & Grier, Inc. Boston, Massachusetts Las Vegas, Nevada Santa Barbara, California
FAA	Federal Aviation Agency Los Angeles, California
GEO-TECH	Geo Technical Corporation Garland, Texas
GIMRADA	U. S. Army Geodesy, Intelligence and Mapping Research and Development Agency Fort Belvoir, Virginia
H-NSC	Hazleton-Nuclear Science Corporation Palo Alto, California
H&N, Inc.	Holmes & Narver, Inc. Los Angeles, California Las Vegas, Nevada
ISOTOPEs	Isotopes, Inc. Westwood, New Jersey
ITEK	ITEK Corporation Palo Alto, California
LPI	Lucius Pitkin, Inc. New York, New York
NBM	Nevada Bureau of Mines University of Nevada, Reno, Nevada
NRDL	U. S. Naval Radiological Defense Laboratory San Francisco, California
REECo	Reynolds Electrical & Engineering Co., Inc. Las Vegas, Nevada
SC	Sandia Corporation Albuquerque, New Mexico
SRI	Stanford Research Institute Menlo Park, California

RFB, Inc.	R. F. Beers, Inc. Alexandria, Va.
STL	Space Technology Laboratories, Inc. Redondo Beach Park, California
TI	Texas Instruments, Inc. Dallas, Texas
USBM	U. S. Bureau of Mines Washington, 25, D. C.
USEM-PRC	U. S. Bureau of Mines Bartlesville Petroleum Research Center Bartlesville, Oklahoma
USC&GS	U. S. Coast and Geodetic Survey Las Vegas, Nevada
USGS	U. S. Geologic Survey Denver, Colorado
USPHS	U. S. Public Health Service Las Vegas, Nevada
USWB	U. S. Weather Bureau Las Vegas, Nevada
WES	Waterways Experiment Station U. S. Army Engineers Vicksburg, Mississippi